"METHODS OF LESSENING THE CONSUMPTION OF STEAM, AND, CONSEQUENTLY OF FUEL, IN FIRE-ENGINES"

James Watt was more than just an inventor. Watt's discoveries were remarkable as they came in a period when a satisfactory theory of heat was still a generation away. Watt's genius lies in combining experimental science with practical application. His discovery of the condensor which made the industrial revolution possible is a classical example of the scientific method. This story is told in the words of James Watt himself, and his companion of that period, Professor Robison.

Prepared by Professor G. Kardos, McMaster University, Hamilton, Ont. Canada, with support from the National Science Foundation.

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Thermodynamics to 1769

In 1760 the science of thermodynamics was in its infancy. The invention of the thermometer in 1592 had made the science possible. The two finite point method of calibrating the thermometer had been tried in 1694, resulting in the development of the Fahrenheit scale in 1717 and the Centigrade scale in 1740.

The thermometer provided not only the means of making thermometric measurements but ushered in the new science. One of the chief architects of the new science was Joseph Black, a professor at Glasgow between 1756 and 1766, and a close associate of James Watt. Between the years 1759 and 1762 he made his main discoveries in heat. Until Black, there was no clear distinction in people's minds between the concept of "quantity of heat" and "degree of hotness." Black's work made the distinction sharp and conceived clearly of heat as a measurable physical quantity.

In the year 1760 Black first investigated the heating of different bodies and between then and 1762 discovered the concept of "specific heat." By 1762 he was able to present his ideas on specific heat and his discovery of "latent heat" to the Philosophical Club at the University of Glasgow.

Only this meager science was avilable to Watt. In fact, he contributed to demonstrating its soundness.

The mechanical equivalent of heat was not to be discovered and announced by [redacted] until 1798, although Watt's necessary definition of power and its equivalent to coal burned predated these discoveries by many years.

Rumford

Steam Power

The origin of steam as a source of power lies not with steam but with the use of air. Steam was only considered as a means of producing a vacuum on which atmospheric pressure would act to produce power.

Otto Von Guericke in 1650 at Magdeborg demonstrated that evacuating a cylinder could cause a piston to move into a cylinder even when restrained by fifty men; thus demonstrating that work could be done by an engine if a vacuum were drawn under a piston. The Dutch philosopher Huyghens in 1680 designed an engine to use gun powder as motive power. This consists of a cylinder piston arrangement in which gun powder is burned. This was never developed into a practical machine.

Denis Papin, an acquaintance of Huyghens and a colleague of Robert Boyle's, about 1690 developed Huyghens' idea further by substituting water for gunpowder in the cylinder and heating it to expel the air. The cylinder was then cooled and the piston moved under atmospheric pressure to do work. Papin built a model and demonstrated that the idea was feasible. He was faced with the common problem of the times, crude workmanship. He could not get truly turned cylinders of any appreciable size. Furthermore, his use of a single element to act as a cylinder and boiler precluded the device from becoming practical.

The first commercial use of steam was by

Thomas Savery, an English military engineer. In 1698 he received a patent for "A New Invention for Raising Water and Occasioning All Sorts of Mill Work by the Impelling Force of Fire." The invention (Exhibit 1) was a steam pump; the steam from a separate boiler was admitted into a closed vessel and condensed by cold water poured on the outside. The resultant vacuum drew water up the suction pipe through a non-return valve. When steam was again admitted, the water was forced out of the vessel through another non-return valve and up the forcing pipe. The steam and cold water were controlled by hand operated valves. Although theoretically sound, the pump was unreliable, inefficient, and dangerous. The need to use steam above atmospheric pressure was hazardous with the primitive boilers available. Savery's pumps were made, but not for the purpose originally intended–the draining of coal and tin mines.

Thomas Newcomen of Dartmouth, England, meanwhile was at work on the pressing needs of the Cornish mines for power for pumping. He pursued his experiments for 15 years, and erected his first engine in 1712. Newcomen's engine (Exhibit 2) was to have a steam-induced vacuum drawn down the piston in a cylinder, as in Papin's engine. A separate boiler was valved to admit steam to the cylinder while the piston was moving to the top. The admission of steam was to exclude air from the cylinder and drive water out of the cylinder. When the piston had reached the top of its stroke, the steam valve was closed and cold water was sprayed directly into the cylinder to condense the steam. The injection of water directly into the cylinder was a much more effective arrangement than cooling the outside of the cylinder. The resultant vacuum caused the piston to move down, due to atmospheric pressure. This engine was often referred to as an atmospheric engine. Water was provided to the top of the piston to act as a seal between the piston and cylinder. A mechanism was provided to operate the valves in sequence.

Newcomen had no formal training. John Theophilius Desagulies, in 1744, gave an account of Newcomen's invention,

> About the year 1710 Thomas Newcomen, iron manager, and John Calley, a glazier...made several experiments in private, and having brought their engine to work with a piston, etc., in the latter part of 1711 made proposals to draw water.... after a great many laborious attempts, they did make the engine work; but not being either philosophers to understand the reasons, or mathematicians enough to calculate the powers and to proportion the parts, very luckily by accident found what they sought.... The engine was rendered self-acting by the ingenuity of Humphrey Pottes, a boy employed to mind the engine, who contrived a series of catches and strings worked from the beam, by which the several valves were opened and closed in due order.

Newcomen's invention could not be exploited except by arrangement with Savery whose patent covered the raising of water by fire. On Savery's death in 1715 an agreement was reached between Newcomen

and Savery's heirs. Newcomen's engine rapidly came into use for mine pumping—first in England then throughout Europe.

Owing to the low pressure steam used, there was no difficulty in making any part of the engine except the cylinder. The demand for the engine spurred the development of better means of manufacturing larger and more accurate cylinders.

Thomas Newcomen died in 1729, seven years before the birth of James Watt in 1736.

Discovery & Invention

James Watt was born in Greenoch, Scotland, the son of a small merchant. To learn instrument making he had to travel to London and serve his apprenticeship there. Because of professional jealousies he was not allowed to practice his craft on his return to Glasgow. He therefore became a mathematical instrument maker at the University in 1757. It was here that he was first encountered by John Robison, then a student.

Professor John Robison recalls his meetings with Watt:

"My acquaintance with Mr. Watt began in 1758. I was then a student in the University of Glasgow, and studying the science which I now profess to teach, Natural Philosophy....Mr. Watt came to settle in Glasgow as a mathematical and philosophical instrument maker, and was employed to repair and set up a very noble collection of instruments bequeathed to the University.... Mr. Watt had apartments and a workshop within the College.... I was eager to be acquainted with the practice of astronomical observation and my wishes were much encouraged by....gentlemen eminent for their mathematical abilities. Those gentlemen brought me with them into Mr. Watt's shop; and when he saw me thus patronized, or introduced, his natural complaisance made him readily indulge my curiosity.

. . . .

After first feasting my eyes with the view of fine instruments, and prying into everything, I conversed with Mr. Watt. I saw a workman and expected no more; but was surprised to find a philosopher, as young as myself, and always ready to instruct me. I had the vanity to think myself a pretty good proficient in my favorite study, and was rather mortified at finding Mr. Watt so much my superior. But his own high relish for those things made him pleased with the chat of any person who had the same tastes with himself, or his innate complaisance made him indulge my curiosity, and even encourage my endeavors to form a more intimate acquaintance with him. I lounged much about him, and, I doubt not, was frequently teasing him. Thus our acquaintance began.

"In 1759, I left the College for the navy *(in 1763 I)* returned to my academic habits. I was happy to find Mr. Watt settled in Glasgow, as fond of science as ever. Our acquaintance was renewed; I believe with mutual satisfaction, for I had now acquired some knowledge...I found him as good and kind as ever, as keen after the acquisition of knowledge, and well disposed to listen to the information I could give him concerning things which had not fallen in his own way. But I found him continually striking into untrodden paths, where I was always obliged to be a follower....

"I had had the advantage of a more regular education: this frequently enabled me to direct or confirm Mr. Watt's speculations,

and put into a systematic form the random suggestions of his inquisitive and inventive mind...Whenever any puzzle came in the way of any of us, we went to Mr. Watt. He needed only to be prompted; everything became to him the beginning of a new and serious study; and we knew that he would not quit it till he had either discovered its insignificance, or had made something of it. ...Hardly any projects, such as canals, deepening the river, surveys, or the like, were undertaken in the neighborhood without consulting Mr. Watt; and he was even importuned to take the charge of some considerable works of this kind, though they were such as he had not the smallest experience in...But this superiority was concealed under the most amiable candour, and liberal allowance of merit to every man. Mr. Watt was the first to ascribe to the ingenuity of a friend things which were very often nothing but his own surmises, followed out and embodied by another. I am well entitled to say this, and have often experienced it in my own case

....

"And I cannot here pass over another circumstance which endeared Mr. Watt to us all: he was without the smallest wish to appropriate knowledge to himself; and one of his greatest delights was to set others on the same road to knowledge with himself. No man could be more distant from the jealous concealment of a tradesman; and I am convinced that nothing but the magnitude of the prospect which his improvement of the steam-engine held out to him and his family, could have made Mr. Watt refuse himself the pleasure of communicating immediately all his discoveries to his acquaintances. Nay, he could *not* conceal it; for, besides frankly imparting it to Dr. Black, to myself, and two or three more intimate friends, he disclosed so much of what he had been doing, that had it been in London or Birmingham, I am confident that two or three patents would have been expedited, for bits of his method, by bustling tradesmen, before he (would have) thought himself entitled to solicit such a thing.

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"I doubt not but all this will be looked upon by some as mere panegyric. The ignorant are insensible to the pleasures of science, and have no notion of the attachments which this may produce; and the low-bred minds whose whole thoughts are full of concealment, rivalship, and money-making, can hardly conceive a mind that is not actuated by similar propensities."

James Watt describes his discovery as follows:

"My attention was first directed, in the year 1759, to the subject of steam-engines by Dr. Robison, then a student at the University of Glasgow, and nearly of my own age. He at that time threw out an idea of applying the power of the steam-engine to the moving of wheel carriages, and to other purposes; but the scheme was not matured, and was soon abandoned on his going abroad.

"About the year 1761, or 1762, I tried some experiments on the force of steam in a Papin's digester *(pressure cooker)* and formed a species of steam-engine by fixing upon it a syringe, one-third of an inch diameter, with a solid piston, and furnished also with a cock to admit the steam from the digester, or shut it off at pleasure, as well as to open a communication from the inside of the syringe to the open air, by which the steam contained in the syringe might escape. When the communication between the digester and syringe was opened, the steam entered the syringe, and

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by its action upon the piston raised a considerable weight (15 lbs.) with which it was loaded. When this was raised as high as was thought proper, the communication with the digester was shut, and that with the atmosphere opened; the steam then made its escape, and the weight descended. The operations were repeated, and, though in this experiment the cock was turned by hand, it was easy to see how it could be done by the machine itself, and to make it work with perfect regularity. But I soon relinquished the idea of constructing an engine upon its principle, from being sensible it would be liable to some of the objections against Savery's engine, viz., the danger of bursting the boiler, and the difficulty of making the jonts tight, and also that a great part of the power of the steam would be lost, because no vacuum was formed to assist the descent of the piston. I, however, described this engine in the fourth article of the specification of my patent of 1769; and again in the specification of another patent in the year 1784, together with a mode of applying it to the moving of wheel-carriages.

"...In the winter of 1763-4, having occasion to repair a model of Newcomen's engine belonging to the University of Glasgow, my mind was again directed to it....I set about repairing it as a mere mechanician; and when that was done, and it was set to work, I was surprised to find that its boiler could not supply it with steam, though apparently quite large enough (the cylinder of the model being two inches in diameter, and six inches stroke, and the boiler about nine inches diameter). By blowing the fire it was made to take a few strokes, but required an enormous quantity of injection water, though it was very lightly loaded by the column of water in the pump. It soon occurred that this was caused by the little cylinder exposing a greater surface to condense the steam, than the cylinders of larger engines did in proportion to their respective contents. It was found that by shortening the column of water in the pump, the boiler could supply the cylinder with steam, and that the engine would work regularly with a moderate quantity of injection. It now appeared that the cylinder of the model, being of brass, would conduct heat much better than the cast-iron cylinders of larger engines (generally covered on the inside with a stony crust), and that considerable advantage could be gained by making the cylinders of some substance that would receive and give out heat slowly. Of these, wood seemed to be the most likely, provided it should prove sufficiently durable. A small engine was, therefore, constructed, with a cylinder six inches diameter, and twelve inches stroke, made of wood, soaked in linseed oil, and baked to dryness. With this engine many experiments were made; but it was soon found that the wooden cylinder was not likely to prove durable, and that the steam condensed in filling it still exceeded the proportion of that required for large engines, according to the statements of Desaguliers. It was also found that all attempts to produce a better exhaustion by throwing in more injection, caused a disproportionate waste of steam. On reflection, the cause of this seemed to be the boiling of water in vacuo at low heats, a discovery lately made by Dr. Cullen and some other philosophers (below 100°, as I was then informed); and consequently, at greater heats, the water in the cylinder would produce a steam which would, in part, resist the pressure of the atmosphere.

"By experiments which I then tried upon the heats at which water boils under several pressures greater than that of the atmo-

sphere, it appeared that when the heats proceeded in an arithmetical, the elasticities proceeded in some geometrical ratio; and, by laying down a curve from my data, I ascertained the particular one near enough for my purpose. It also appeared, that any approach to a vacuum could only be obtained by throwing in large quantities of injection, which would cool the cylinder so much as to require quantities of steam to heat it again, out of proportion to the power gained by the more perfect vacuum; and that the old engineers had acted wisely in contenting themselves with loading the engine with only six or seven pounds on each square inch of the area of the piston.... *(To determine the bulk of steam),* a Florence flask, capable of containing about a pound of water, had about one ounce of distilled water put into it; a glass tube was fitted into its mouth, and the joining made tight by lapping that part of the tube with pack-thread, covered with glazier's putty. *(Exhibit 3)* When the flask was set upright, the tube reached down near to the surface of the water, and in that position the whole was placed in a tin reflecting oven before a fire, until the water was wholly evaporated, which happened in about an hour, and might have been done sooner had I not wished the heat not much to exceed that of boiling water. As the air in the flask was heavier than the steam, the latter ascended to the top, and expelled the air through the tube. When the water was all evaporated, the oven and flask were removed from the fire, and a blast of cold air was directed against one side of the flask, to collect the condensed steam in one place. When all was cold, the tube was removed; the flask and its contents were weighed with care; and the flask being made hot, it was dried by blowing into it by bellows, and then weighed again, was found to have lost rather more than four grains, estimated at 4-1/3 grains. When the flask was filled with water, it was found to contain about 17-1/8 ounces avoirdupois of that fluid, which gave about 1800 for the expansion of water converted into steam of the heat of boiling water.

"This experiment was repeated with nearly the same result; and in order to ascertain whether the flask had been wholly filled with steam, a similar quantity of water was for the third time evaporated; and, while the flask was still hot, it was placed inverted, with its mouth (contracted by the tube) immersed in a vessel of water, which it sucked in as it cooled, until in the temperature of the atmosphere it was filled to within half an ounce measure of water. In the contrivance of this experiment I was assisted by Dr. Black. In Dr. Robison's edition of Dr. Black's Lectures, vol. i., p. 147, the latter hints at some experiments upon this subject, as made by *him*; but I have no knowledge of any except those which I made myself.

"In repetitions of this experiment at a later date, I simplified the apparatus by omitting the tube and laying the flask upon its side in the oven, partly closing its mouth by a cork, having a notch on one side, and otherwise proceeding as has been mentioned.

"I do not consider these experiments as extremely accurate, the only scale-beam of a proper size which I had then at my command not being very sensible, and the bulk of the steam being liable to be influenced by the heat to which it is exposed, which, in the way described, is not easily regulated or ascertained; but, from my experience in actual practice, I esteem the expansion to be rather more than I have computed.

"A boiler was constructed which showed, by inspection, the quantity of water evaporated in any given time, and thereby ascertained the quantity of steam used in every stroke by the engine, which I found to be several times the full of the cylinder. Astonished at the quantity of water required for the injection, and the great heat it had acquired from the small quantity of water in the form of steam which had been used in filling the cylinder, and thinking I had made some mistake, the following experiment was tried: *(Exhibit 3)* A glass tube was bent at right angles; one end was inserted horizontally into the spout of a tea-kettle, and the other part was immersed perpendicularly in well-water contained in a cylindric glass vessel, and steam was made to pass through it until it ceased to be condensed, and the water in the glass vessel was become nearly boiling hot. The water in the glass vessel was then found to have gained an addition of about one-sixth part from the condensed steam. Consequently, water converted into steam can heat about six times its own weight of well-water to 212°, or till it can condense no more steam. Being struck with this remarkable fact, and not understanding the reason of it, I mentioned it to my friend Dr. Black, who then explained to me his doctrine of latent heat, which he had taught for some time before this period (summer 1764); but having myself been occupied with the pursuits of business, if I had heard of it, I had not attended to it, when I thus stumbled upon one of the material facts by which that beautiful theory is supported.

"On reflecting further, I perceived that, in order to make the best use of steam, it was necessary—first, that the cylinder be maintained always as hot as the steam which entered it; and, secondly, that when the steam was condensed, the water of which it was composed, and the injection itself, should be cooled down to 100°, or lower, where that was possible. The means of accomplishing these points did not immediately present themselves; but early in 1765...One Sunday afternoon I had gone to take a walk in the Green of Glasgow, and when about half way between the Herd's House and Arn's Well, my thoughts having been naturally turned to the experiments I had been engaged in for saving heat in the cylinder, *at that part of the road* the idea occurred to me, that if a communication were opened between a cylinder containing steam, and another vessel which was exhausted of air and other fluids, the steam, as an elastic fluid, would immediately rush into the empty vessel, and continue so to do until it had established an equilibrium; and if that vessel were kept very cool by an injection, or otherwise, more steam would continue to enter until the whole was condensed. But both the vessels being exhausted, or nearly so, how were the injection-water, the air which would enter with it, and the condensed steam, to be got out? This I proposed, in my own mind, to perform in two ways. One was, by adapting to the second vessel a pipe, reaching downwards more than 34 feet, by which the water would descend (a column of that length overbalancing the atmosphere), and by extracting the air by means of a pump.

"The second method was by employing a pump, or pumps, to extract both the air and the water, which would be applicable in all places, and essential in those cases where there was no well or pit.

"This latter method was the one I then preferred, and is the only one I afterwards continued to use.

"In Newcomen's engine, the piston is kept

tight by water, which could not be applicable in this new method; as, if any of it entered into a partially-exhausted and hot cylinder, it would boil, and prevent the production of a vacuum, and would also cool the cylinder by its evaporation during the descent of the piston. I proposed to remedy this defect by employing wax, tallow, or other grease, to lubricate and keep the piston tight. It next occurred to me, that the mouth of the cylinder being open, the air which entered to act on the piston would cool the cylinder, and condense some steam on again filling it. I therefore proposed to put an air-tight cover upon the cylinder, with a hole and stuffing-box for the piston-rod to slide through, and to admit steam above the piston to act upon it, instead of the atmosphere. The piston-rod sliding through a stuffing-box was new in steam-engines; it was not necessary in Newcomen's engine, as the mouth of the cylinder was open, and the piston-rod was square and very clumsy. The fitting the piston-rod to the piston by a cone was an after-improvement of mine (about 1774). There still remained another source of the destruction of steam, the cooling of the cylinder by the external air, which would produce an internal condensation whenever steam entered it, and which would be repeated every stroke; this I proposed to remedy by an external cylinder, containing steam, surrounded by another of wood, or of some other substance which would conduct heat slowly.

"When once the idea of the separate condensation was started, all these improvements followed as corollaries in quick succession, so that in the course of one or two days the invention was thus far complete in my mind, and I immediately set about an experiment to verify it practically. *(Exhibit 4)* I took a large brass syringe, 1¾ inches diameter and 10 inches long, made a cover and bottom to it of tin-plate, with a pipe to convey steam to both ends of the cylinder from the boiler; another pipe to convey steam from the upper end to the condenser (for, to save apparatus, I inverted the cylinder); I drilled a hole longitudinally through the axis of the stem of the piston, and fixed a valve at its lower end, to permit the water, which was produced by the condensed steam on first filling the cylinder, to issue. The condenser used upon this occasion consisted of two pipes of thin tin-plate, ten or twelve inches long, and about one-sixth inch diameter, standing perpendicular, and communicating at top with a short horizontal pipe of large diameter, having an aperture on its upper side, which was shut by a valve opening upwards. These pipes were joined at bottom to another perpendicular pipe of about an inch diameter, which served for the air and water-pump; and both the condensing pipes and the air-pump were placed in a small cistern filled with cold water. This construction of the condenser was employed from knowing that heat penetrated thin plates of metal very quickly, and considering that if no injection was thrown into an exhausted vessel, there would be only the water of which the steam had been composed, and the air which entered with the steam, or through the leaks, to extract.

"The steam-pipe was adjusted to a small boiler. When steam was produced, it was admitted into the cylinder, and soon issued through the perforation of the rod, and at the valve of the condenser. When it was judged that the air was expelled, the steam -cock was shut, and the air-pump piston-rod was drawn up, which leaving the small pipes of the condenser in a state of vacuum, the steam entered them and was

condensed. The piston of the cylinder immediately rose, and lifted a weight of about 18 lbs., which was hung to the lower end of the piston-rod. The exhaustion-cock was shut, the steam was readmitted into the cylinder, and the operation was repeated; the quantity of steam consumed, and the weights it could raise, were observed; and, excepting the non-application of the steam-case and external covering, the invention was complete, insofar as regarded the savings of steam and fuel. A large model, with an outer cylinder and wooden case, was immediately constructed, and the experiments made with it served to verify the expectations I had formed, and to place the advantage of the invention beyond the reach of doubt. It was found convenient afterwards to change the pipe-condenser for an empty vessel, generally of a cylindrical form, into which an injection played, and, in consequence of there being more water and air to extract, to enlarge the air-pump.

"The change was made, because, in order to procure a surface sufficiently extensive to condense the steam of a large engine, the pipe-condenser would require to be very voluminous, and because the bad water with which engines are frequently supplied would crust over the thin plates, and prevent their conveying the heat sufficiently quick. The cylinders were also placed with their mouths upwards, and furnished with a working-beam, and other apparatus, as was usual in the ancient engines; –the inversion of the cylinder, or rather of the piston-rod, in the model, being only an expedient to try more easily the new invention, and being subject to many objections in large engines.

Professor John Robison once more, takes up the narrative:

"In 1765 I went to the country. About a fortnight after this, I came to town, and went to have a chat with Mr. Watt, and to communicate to him some observations I had made on Desaguliers' and Belidor's account of the steam-engine. I came into Mr. Watt's parlour without ceremony, and found him sitting before the fire, having lying on his knee a little tin cistern, which he was looking it. I entered into conversation on what we had been speaking of at last meeting, –something about steam. All the while, Mr. Watt kept looking at the fire, and laid down the cistern at the foot of his chair. At last he looked at me, and said briskly, 'You need not *fash* yourself any more about that, man; I have now made an engine that shall not waste a particle of steam. It shall all be boiling hot; –aye, and hot water injected if I please.' So saying Mr. Watt looked with complacency at the little thing at his feet, and, seeing that I observed him, he shoved it away under a table with his foot. I put a question to him about the nature of his contrivance. He answered me rather drily. I did not press him to a further explanation at that time, knowing that I had offended him a few days before by blabbing a pretty contrivance which he had hit on for turning the cocks of the engine. I had mentioned this in presence of an engine-builder, who was going to erect one for a friend of mine; and this having come to Mr. Watt's ears, he found fault with it.

"I was very anxious however, to learn what Mr. Watt had contrived, but was obliged to go to the country in the evening. A gentleman who was going to the same house said that he would give me a place in his carriage, and desired me to wait for him on the walk by the river-side. I went thither, and found Mr. Alexander Brown, a very intimate acquaintance of Mr. Watt's, walk-

ing with another gentleman (Mr. Craig, architect). Mr. Brown immediately accosted me with, 'Well, have you seen Jamie Watt?' 'Yes.' 'He'll be in high spirits now with his engine, isn't he?' 'Yes,' said I, 'very fine spirits.' 'Gad,' says Mr. Brown, 'the condenser's the thing: keep it but cold enough, and you may have a perfect vacuum, whatever be the heat of the cylinder.' The instant he said this, the whole flashed on my mind at once. I did all I could to encourage the conversation, but was much embarrassed. I durst not appear ignorant of the apparatus, lest Mr. Brown should find that he had communicated more than he ought to have done. I could only learn that there was a vessel called a condenser, which communicated with the cylinder, and that this condenser was immersed in cold water, and had a pump to clear it of the water which was formed in it. I also learned that the great difficulty was to make the piston tight; and that leather and felt had been tried, and were found quite unable to stand the heat. I saw that the whole would be perfectly dry, and that Mr. Watt had used steam instead of air to press up his piston, which I thought, by Mr. Brown's description, was inverted....Next day, impatient to see the effects of the separate condensation, I sent to Paisley and got some tin things made there, in completion of the notion that I had formed. I tried it as an air-pump, by making my steam-vessel communicate with a tea-kettle, a condenser, and a glass receiver. In less than two minutes I rarefied the air in a pretty large receiver more than twenty times. I could go no farther in this process, because my pump for taking out the air from my condenser was too large, and not tight enough; but I saw that when applied to the mere purpose of taking out the air generated from the water, the vacuum might be made almost complete. I saw, too (in consequence of a conversation the preceding day with Mr. Watt about the eduction-pipe in Beighton's engine), that a long suck-pipe, or syphon, would take off all the water. In short, I had no doubt that Mr. Watt had really made a perfect steam-engine.

. . . .

"I think it was the middle of winter before I saw Mr. Watt. When we met, he most frankly told me all his contrivance; and I took care to receive it all as perfectly new to me, that I might not commit Mr. Brown. I remember well, that when he complained of the great power expended in working pumps sufficiently large to exhaust a condenser even of moderate size (because they must do it at one stroke against the whole pressure of the atmosphere), I mentioned the observation that I had formerly made to him on the eduction-pipe of Beighton's engine, and the contrivance which I would deduce from it for clearing the condenser of water. Mr. Watt said, 'O man, do you imagine me so dull as not to have thought on that long ago? But I could give you many reasons why it will now answer so well as a pump. I wish I could as quickly get quit of the air as of the water, without a pump. I don't despair even of this.' He now informed me of many curious properties of steam relative to its heat and elasticity, explained his methods of condensation, and mentioned some remarkable facts relative to this subject, which pass to this day before the eyes of everybody, without being noticed or understood by hundreds who call themselves engineers and builders of steam-engines.

"After this time my meetings with Mr. Watt were less frequent.................
But I had now learned all the principles of

Mr. Watt's invention, though I had never seen either his engine or any model or drawing of it. I knew of his employing steam in place of the atmosphere to press forward his piston, although it was long ere I knew the way in which he introduced it. I thought he simply admitted it from the surrounding case by the open mouth of the cylinder; and it was not till I was in St. Petersburgh that I learned that he also introduced it (without a steam-case), by a pipe. This, however, was a *natural* part of the leading thought; and, indeed, was practised by him in his very first experiment.

"In this experiment (which was made with a common anatomist's great injection-syringe for a cylinder), the piston-rod passed through another aperture in the same cover; and it escaped into the condenser by a similar aperture in a cover on the other end of the cylinder. Long after this, I found that the little apparatus which I saw on his knee, and which he shoved under the table with his foot, was the condenser in this first experiment. I discovered that I had not comprehended the whole contrivance so completely as I imagined. But though I was ashamed of my ignorance, my vanity would not let me acknowledge it; and I took circuitous ways of learning more exactly the precise state of the engine. I was living in Edinburgh during the summer of 1767, near Dr. Black....I one day asked him why Mr. Watt never thought of impelling the piston by steam much stronger than common steam, mentioning the way in which I would introduce and manage it. He then corrected me in some parts of my proposed construction, and described Mr. Watt's with accuracy; and bade me reflect on the enormous size and strength which must be given to the boiler, and the expense of fuel in supplying steam so dense and so hot. All this I had thought on already, and only wanted to learn what he had just now told me; and now I am fully entitled to say, that in the summer of 1767 the whole contrivance was perfect in Mr. Watt's mind, although he had neither executed the double stroke, nor that most beautiful contrivance of cutting off the steam before the piston reaches the bottom of the cylinder; a contrivance which in a moment fits the engine, however great and powerful, to any the most trifling task, and makes it more manageable than any other engine whatever that is not immediately actuated by the hand of man...

"During the two following winters, I had many opportunities of conversing with him, and learned all his difficulties and embarrassments. He struggled long to condense with sufficient rapidity without injection, and exhibited many beautiful specimens of ingenuity and fertility of resource. Many pretty schemes occurred to him for a rotatory engine. Some of these I am sorry to find he has neglected.

. . . .

Epilogue

James Watt struggled with the development of his "fire engine." At the recommendation of friends his first application for patent in 1769 was coached in as broad terms as possible (Exhibit 5). He first went into partnership with Dr. Roebuck because of his need for money to develop his engine. In 1773 Roebuck went into bankruptcy, Watt's engine still not fully developed. Matthew Boulton, an industrialist, acquired Roebuck's interest in the engine and formed a partnership with Watt. With Boulton backing Watt finally built his first operating engine in 1776. (Exhibit 6)

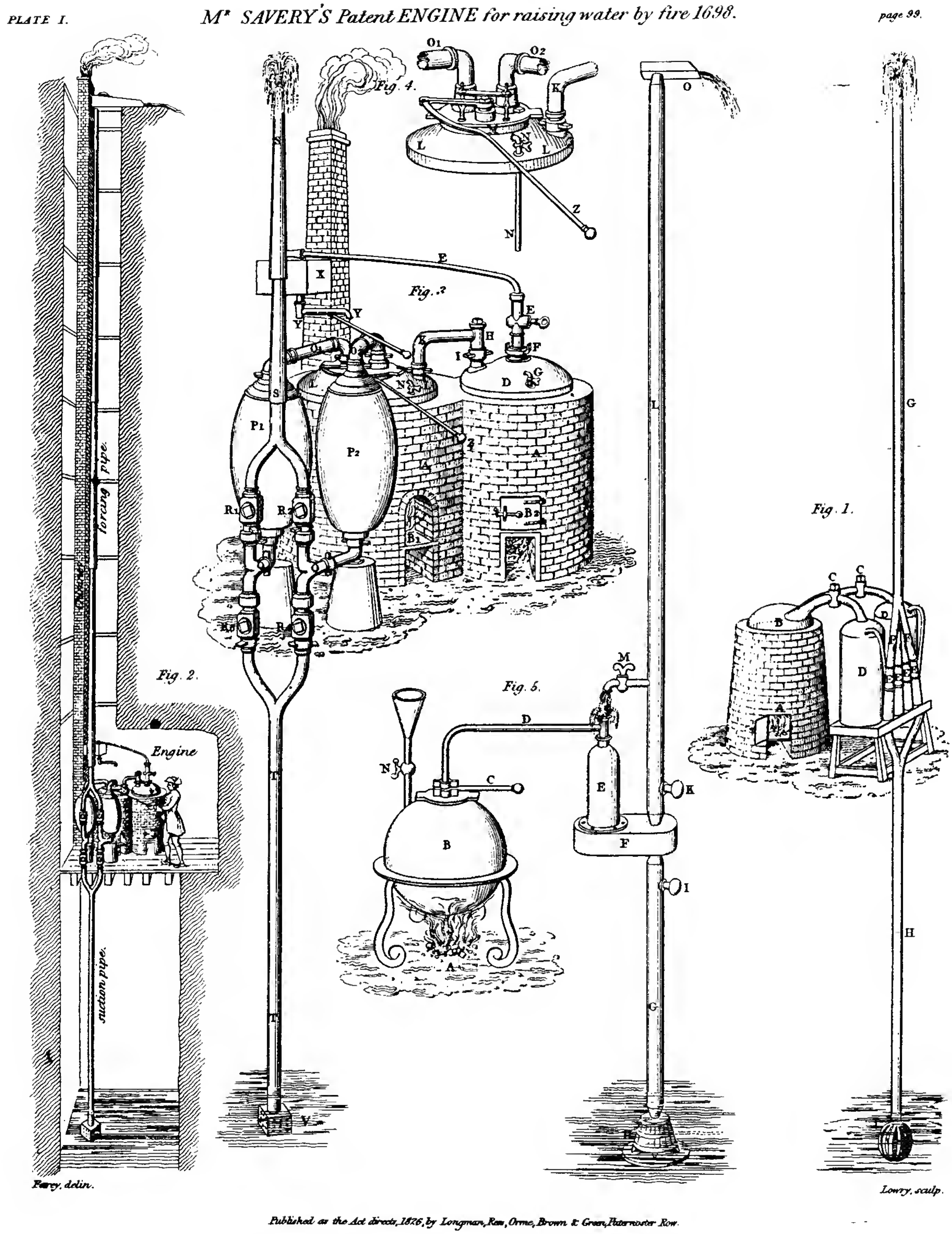


Exhibit 1

Savery's Steam Pump

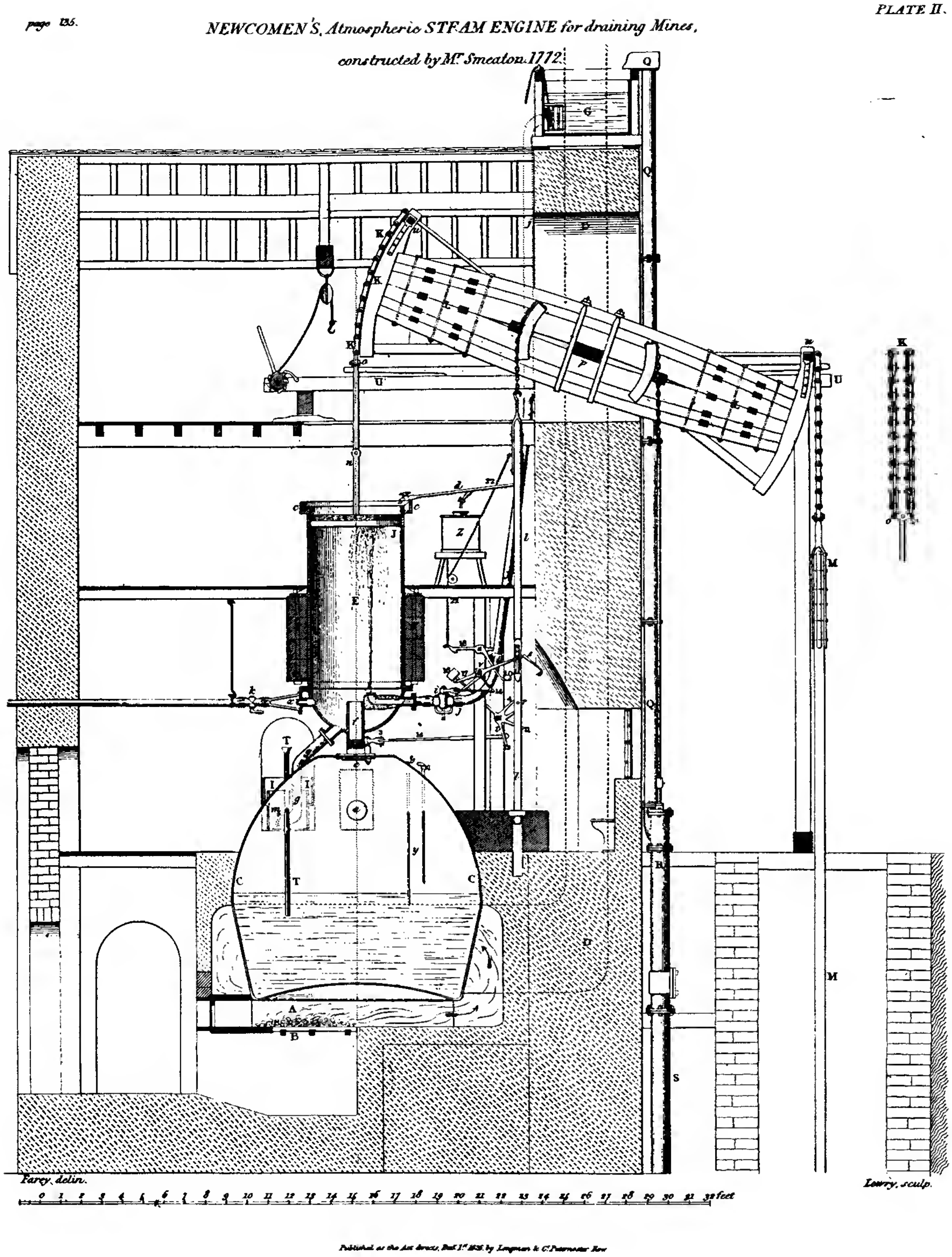
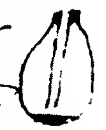
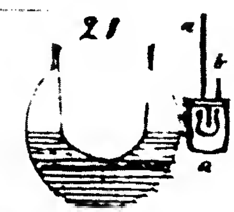


Exhibit 2

Newcomen's Steam Engine

Exp. 1. a Florence Flask with about
an ounce of water it had a glass tube
inserted at its mouth & reaching
near the surface of the water

the tube was wrapt round with
thread so as to fit the mouth of the
Flask & then made tight with putty
it was placed in a White Iron oven
before the fire till the water was intirely
evaporated and as the air was heavier
than the steam it must have been
driven out first as it lay nearest
the mouth of the tube so it may be
concluded that the flask was filled

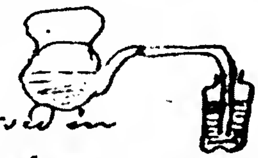


This Vessell made of Copper
having a gage pipe immersed in
a Cistern of Mercury at A. and
a thermometer with its bulb in the
Inside at b. being close shut
excepting a Snifting Valve also at b. to such
Diameter, the Boiling Water point of the Ther

Exhibit 3

Abstracts from Watt's Notebook
(From Reference 2, by permission)

10. I found that ~~that~~ the Quantity of water
used for Injection in fire engines was
much Greater than I thought was
Necessary to Cool the Quantity of water
of water contained in the Steam down
to below the boiling point. I mixed
1 part of boiling water with 30 parts
of Cold water I found it only heated
to the arithmetical mean betwixt the
two heats & that it was scarcely sensibly
heated to the finger.
I took a bent Glass tube & inserted it into
the nose of a tea kettle



the other end being immersed in
Cold water I found ~~a small increase of the~~
~~water in the~~ the on making the
kettle boil that tho there was only
a small increase of the water in
Refrigeratory that it was become
boiling hot, this I was surprized at
& on telling it to Dr Black & asking
him if it was possible that water
under the form of steam could contain
more heat than it did when water

Exhibit 3

Abstract from Watt's Notebook
(From Reference 2, by permission)

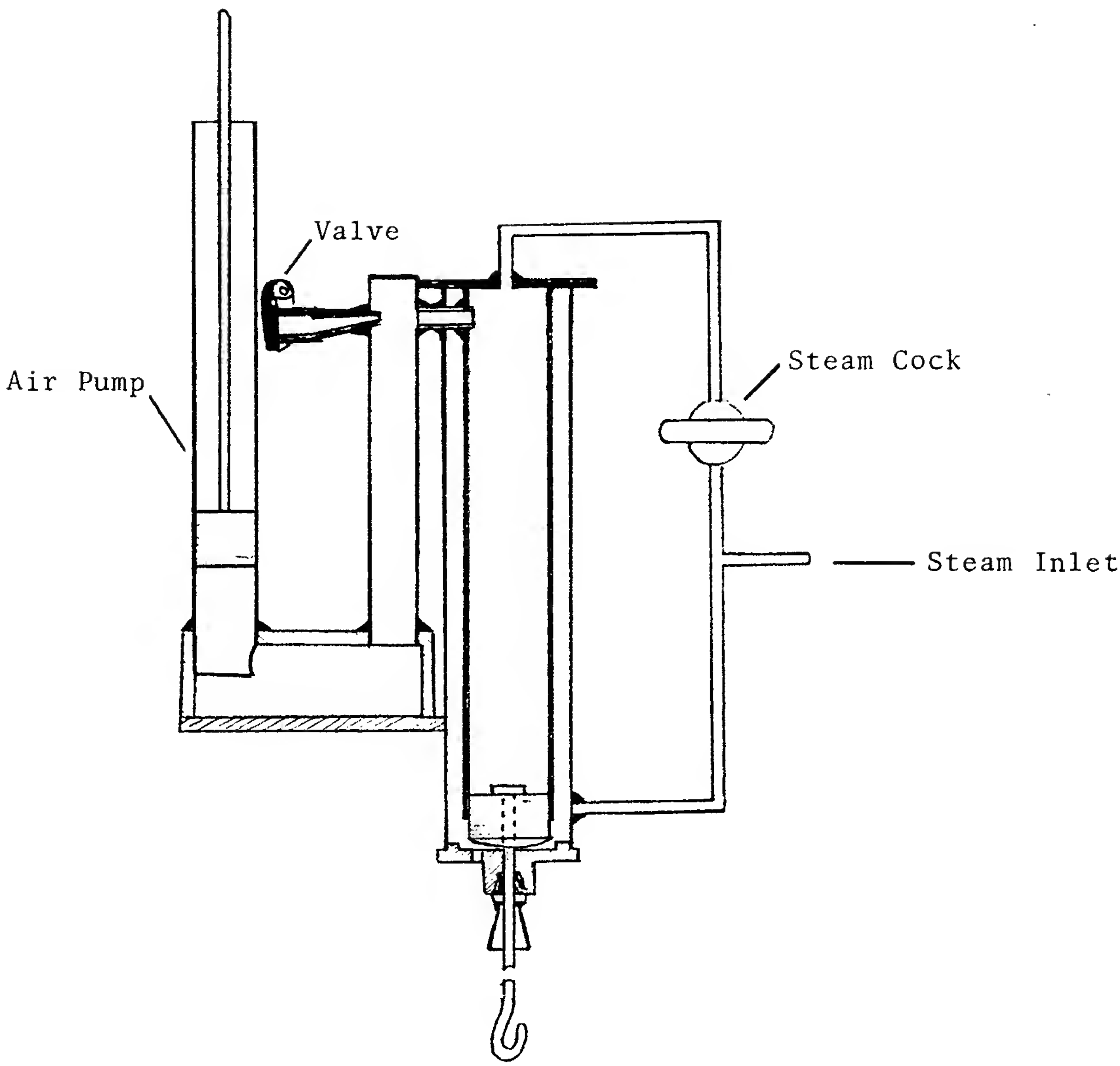


Exhibit 4

Diagram of Watt's Surface Condenser Model

SPECIFICATION OF PATENT, JANUARY 5TH, 1769, FOR A NEW METHOD OF LESSENING THE CONSUMPTION OF STEAM AND FUEL IN FIRE ENGINES.

TO ALL TO WHOM these presents shall come, I, JAMES WATT, of Glasgow, in Scotland, Merchant, send greeting.

WHEREAS His Most Excellent Majesty King George the Third, by his Letters Patent, under the Great Seal of Great Britain, bearing date the fifth day of January, in the ninth year of his said Majesty's reign, did give and grant unto me, the said JAMES WATT, his special licence, full power, sole privilege and authority, that I, the said JAMES WATT, my executors, administrators, and assigns, should, and lawfully might, during the term of years therein expressed, use, exercise, and vend throughout that part of his Majesty's Kingdom of Great Britain called England, the Dominion of Wales, and Town of Berwick upon Tweed, and also in his Majesty's Colonies and Plantations abroad, my new invented 'METHOD OF 'LESSENING THE CONSUMPTION OF STEAM AND FUEL IN FIRE ENGINES;' in which said recited Letters Patent is contained a Proviso, obliging me, the said JAMES WATT, by writing under my hand and seal, to cause a particular description of the nature of the said invention to be inrolled in his Majesty's High Court of Chancery, within four calendar months after the date of the said recited Letters Patent, as in and by the said Letters Patent and the Statute in that behalf made, relation being thereunto respectively had, may more at large appear:

NOW KNOW YE, that in compliance with the said Proviso, and in pursuance of the said Statute, I, the said JAMES WATT, do hereby declare that the following is a particular description of the nature of my said invention and the manner in which the same is to be performed (that is to say): MY METHOD of lessening the consumption of steam, and consequently fuel, in fire engines, consists of the following principles:

FIRST, that vessel in which the powers of steam are to be employed to work the engine, which is called the *Cylinder* in common fire engines, and which I call the *Steam Vessel*, must, during the whole time the engine is at work, be kept as hot as the steam that enters it; first, by inclosing it in a case of wood, or any other materials that transmit heat slowly; secondly, by surrounding it with steam or other heated bodies; and, thirdly, by suffering neither water nor any other substance colder than the steam to enter or touch it during that time.

SECONDLY, in Engines that are to be worked wholly or partially by condensation of steam, the steam is to be condensed in vessels distinct from the steam vessels or cylinders, although occasionally communicating with them: these vessels I call *Condensers*; and, whilst the engines are working, these condensers ought at least to be kept as cold as the air in the neighbourhood of the engines, by application of water, or other cold bodies.

THIRDLY, whatever air, or other elastic vapour, is not condensed by the cold of the condenser, and may impede the working of the engine, is to be drawn out of the steam vessels or condensers by means of pumps, wrought by the engines themselves, or otherwise.

FOURTHLY, I intend in many cases to employ the expansive force of steam to press on the pistons, or whatever may be used instead of them, in the same manner as the pressure of the atmosphere is now employed in common fire engines: in cases where cold water can-

Exhibit 5

Watt's First Application for Engine Patent

not be had in plenty, the engines may be wrought by this force of steam only, by discharging the steam into the open air after it has done its office.

FIFTHLY, where motions round an axis are required, I make the steam vessels in form of hollow rings, or circular channels, with proper inlets and outlets for the steam, mounted on horizontal axles, like the wheels of a water-mill; within them are placed a number of valves, that suffer any body to go round the channel in one direction only: in these steam vessels are placed weights, so fitted to them as entirely to fill up a part or portion of their channels, yct rendered capable of moving freely in them by the means hereinafter mentioned or specified. When the steam is admittcd in thesc engines, between these weights and the valves, it acts equally on both, so as to raise the weight to one side of the wheel, and by the re-action on the valves successively, to give a circular motion to the wheel, the valves opening in the direction in which the weights are pressed, but not in the contrary: as the steam vessel moves round, it is supplied with steam from the boiler, and that which has performed its office may either be discharged by means of condensers, or into the open air.

SIXTHLY, I intend, in some cases, to apply a degree of cold not capable of reducing the steam to water, but of contracting it considerably, so that the engines shall be worked by the alternate expansion and contraction of the steam.

LASTLY, instead of using water to render the piston, or other parts of thc engines, air and steam-tight, I employ oils, wax, resinous bodies, fat of animals, quicksilver, and other metals, in their fluid state.

IN WITNESS whereof I have hereunto set my hand and seal this twenty-fifth day of April, in the year of our Lord one thousand seven hundred and sixty-nine.

JAMES WATT.

Sealed and delivered in the presence of

COLL. WILKIE.
GEO. JARDINE.
JOHN ROEBUCK.

BE IT REMEMBERED, that the said JAMES WATT doth not intend that anything in the Fourth Article shall be understood to cxtend to any engine where the water to be raised enters the steam vessel itself, or any vessel having an open communication with it.

JAMES WATT.

Witnesses. COLL. WILKIE.
GEO. JARDINE.

INROLLED the twenty-ninth day of April, in the year of our Lord one thousand seven hundred and sixty-nine.

Exhibit 5

Watt's First Application for Engine Patent

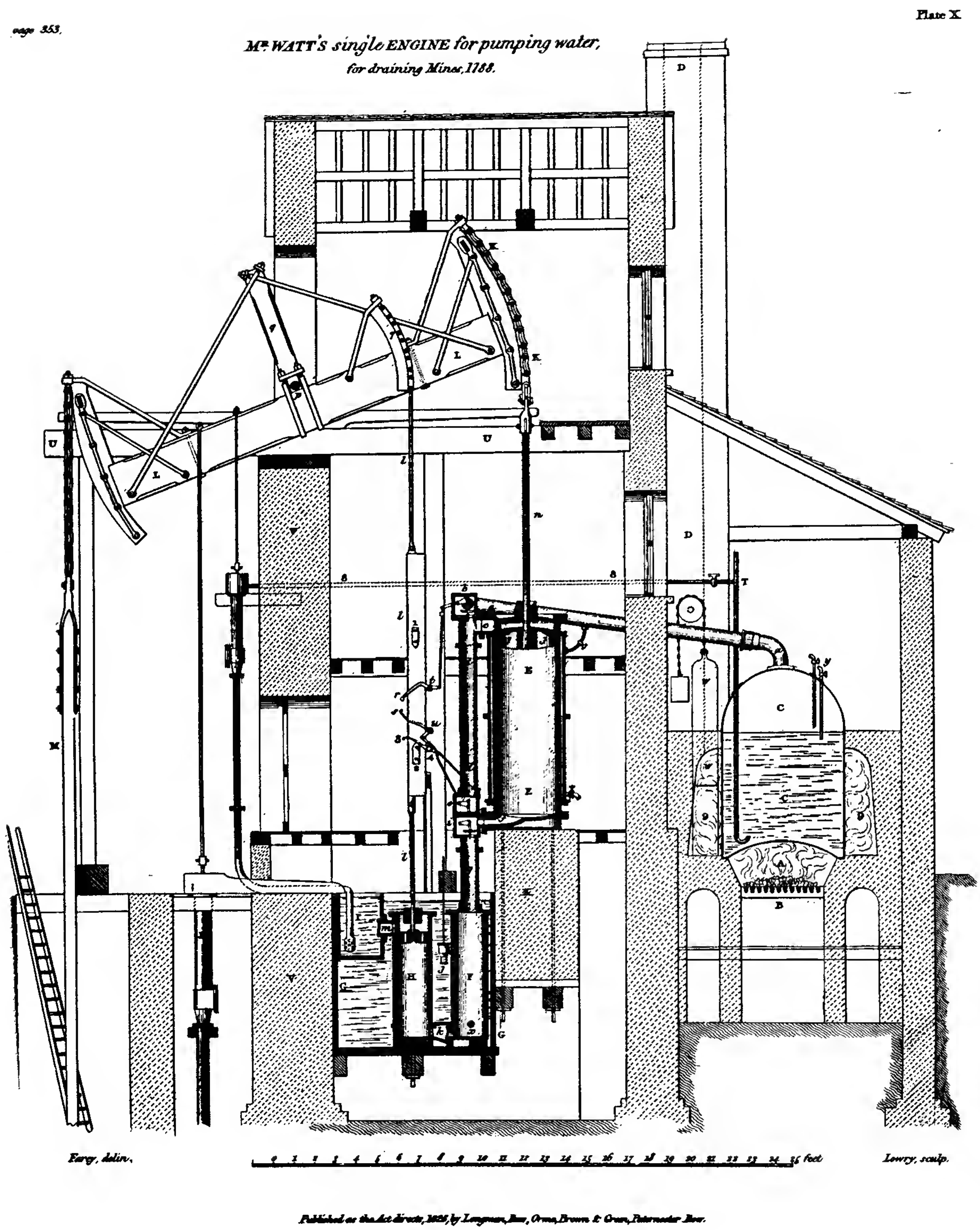


Exhibit 6

Watt's First Engine

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